OUTDOOR-INDOOR CORROSION OF AISI 1010 STEEL IN UMP PEKAN

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ABSTRACT

This project intends to study the outdoor and indoor atmospheric corrosion behavior of AISI 1010 steel over time of exposure in University Malaysia Pahang, Pekan. The project is an experimental analysis in which exposure tests were carried out in accordance to ASTM G1 and ASTM G50. The AISI 1010 steel were exposed for a total of 6 weeks from 1st March 2012 to 12th April 2012. In order to determine and evaluate the atmosphere characteristics, the atmospheric temperature, dew point temperature and relative humidity were monitored. The corrosion products were observed by visually and SEM analysis. It is found that the lepidocrocite and geothite are the major constituents of the corrosion product. Furthermore, the corrosion rate was obtained from the mass loss by applying the equation accordance to ASTM G50. It is noted that the mass loss of both indoor and outdoor atmosphere is increased but tended to stabilize over exposure time. However, the corrosion rate of the outdoor atmosphere is found higher compared to indoor exposure. As a result, the corrosion rate of AISI 1010 steel which exposed at University Malaysia Pahang, Pekan depends mainly on the type of atmospheres rather than time of exposure.

ABSTRAK

Projek ini bertujuan untuk mengkaji pengaratan AISI 1010 di atmosfera luaran dan dalaman di Universiti Malaysia Pahang, Pekan. Projek ini adalah satu analisis eksperimen yang mengikut piawaian ASTM G1 dan G50. Spesimen AISI 1010 telah didedah di atmosfera luaran dan dalaman selama 6 minggu, iaitu bermula dari 1 Mac 2012 hingga 12 April 2012. Pada masa yang sama, suhu atmosfera, suhu titk embun and kelembapan relatif telah diukur untuk menilai ciri-ciri atmosfera. Bahan pengaratan yang terbentuk pada spesimen telah diperhatikan dengan visual and analisis SEM. Ia didapati, lepidocrocite dan geothite adalah juzuk utama yang dijumpai dalam bahan pengarat. Selain itu, kadar pengaratan telah dikira daripada perbezaan jisim spesimen dengan mengunakan rumus yang dinyatakan di ASTM G50. Kehilangan jisim spesimen yang terdedah di kedua-dua luaran dan dalaman atmosfera adalah meningkat tetapi akan menjadi stabil dengan masa pendedahan. Walau bagaimanapun, kadar pengaratan yang terdedah di atmosfera luaran adalah didapati lebih tinggi berbanding dengan atmosfera dalaman. Maka, kadar pengaratan AISI 1010 di Universiti Malaysia Pahang adalah lebih bergantung kepada jenis atmosfera daripada masa pendedahan.

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LIST OF SYMBOLS

a	constant of power law function
A	area in milimeter
D	density in g/mm^3
k	mass loss in g/m^2
K	constant given at 8.76×10^7
n	exponential coefficient
R	correlation coefficient
t	time of exposure in weeks
T	time of exposure in hours
T_{aw}	water vapor on the surface
T_{tw}	time of wetness
T_{ph}	water phase layer
W	mass loss in gram

LIST OF ABBREVIATIONS

AISI	American Iron and Steel Institute
ASTM	American Society for Testing and Materials
BBC	body-centered cubic
C	Carbon
Cl	Chlorine
Cr	Chromium
FCC	face-centered cubic
Fe	Iron
FHWA	United State Federal Highway Admistration
GDP	Gross Domestic Product
H	Hydrogen
ISO	International Standard Organization
Mn	Manganese
N	Nitrogen
Na	Sodium
NACE	National Association of Corrosion Engineers
NCCA	National Coil Coaters Association
P	Phosphorus
S	Sulfur
SAE	Society of Automotive Engineer
SEM	Scanning Electron Microscope
Si	Silicon
UMP	University Malaysia Pahang

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Atmospheric corrosion of metal is an inevitable foe that could not be ignored. Because of the reasons of safety, economic and conservation, attentions are drawn to many countries on the study of atmospheric corrosion in the 21st century. Therefore, in the past decades, many efforts had been expended and undertaken in corrosion study and control at the design stage as well as in the operational phase.

The annual cost and the wasteful depletion of resources due to corrosion in a nation are inconceivable. The cost of protection against atmospheric corrosion has been estimated approximately 50 % of the total cost of all corrosion protection (Schweitzer, 2007). With the large number of outdoor structure such as towers, bridges, vehicles, buildings and other applications which exposed to the atmospheric environment, it is certainly much attention has been given. A survey from World Corrosion Organization stated that the worldwide annual direct cost of corrosion is between € 1.3 trillion and € 1.4 trillion, or 3.1 % to 3.5 % of a nation's Gross Domestic Product (GDP) (Hays, 2010). However, these figures indicate only the cost of reparation, maintenance and replacement but do not include the cost of other losses such as loss of production, resources and damages.

Furthermore, another study that conducted by CC technologies Laboratories, Inc., with the support from the United State Federal Highway Administration (FHWA) and the National Coil Coaters Association (NACE) from year 1999 to 2001, estimated that the total annual direct cost of corrosion in 1998 in the United State to be $276

billion. This is approximately 3.1 % of the United State's Gross Domestic Product (GDP). Among which sector majorly contributed to the total cost of corrosion in industry categories of $137.9 billion in United State is utilities (34.7 %) which includes the electricity utilities, gas utilities, and drinking water and sewer systems. Furthermore, it is followed by transportation (21.5 %), infrastructure (16.4 %), government (14.6 %), and production and manufacturing (12.8 %). These figures also show that the sectors that have higher annual direct cost of corrosion were those commonly exposure to the atmosphere.

Pure iron is very soft and low in strength material. With the addition of moderate amount of carbon can enhance the steel properties. Most of the commercial steels can be classified as low, medium and high carbon steel due to the carbon contents. The properties such as strength, cost and ease of fabrication are the primary considerations for carbon steel application. However, the atmospheric corrosion of conventional carbon steel that would reduces the life of metallic structure and design is always not preferable. Nevertheless, addition of alloy elements such as copper can improve the atmospheric corrosion rate by one quarter or even by one half compare to the conventional carbon steel (Cardarelli, 2008). AISI 1010 steel is ideal especially for automobile industry and general structure application. It is noted that the application of AISI 1010 steel is mainly exposed to the atmosphere. Therefore the study of atmospheric corrosion of AISI 1010 steel is a significant subject and an issue of global concern.

Corrosion is a degradation process of a metal's properties and mass over time. The failure in term of cost and tonnage of atmospheric corrosion is considered more than other type of material degradation processes. There are many variables that may lead to atmospheric corrosion. These comprise of relative humidity, climatic, sulfur dioxide content, chloride content, amount of rainfall, temperature, solar radiation and even the geographic location (Schweitzer, 2007). However, prediction and analysis of atmospheric corrosion becomes difficult with the complexity and diverse nature of the atmospheric pollutant (Syed, 2006).

The existing organizations active in the standardization and development of corrosion test include the American Society of Testing and Material (ASTM), National Association of Corrosion Engineers (NACE), the Society of Automotive Engineer (SAE), the International Standard Organization (ISO) and the National Coil Coaters Association (NCCA) (Davis, 2001).

1.2 PROBLEM STATEMENTS

Atmospheric corrosion mainly depends on the atmosphere condition such as the presence of atmosphere pollutants and the airborne salinity. However, atmospheric conditions vary at different geographic location and environment in which it is generally can be categorized into 4 different types. These include rural, marine, industrial and indoor corrosion. Nevertheless, corrosion rate of steel is also principally influenced by the time of wetness which depends on climatic factors of the region such as temperature, amount of rainfall and relative humidity.

Although there are many researches and studies had been carried out in the past few decades at different areas and locations in order to investigate the relationship of atmosphere and corrosion rate of steel, but there is still no accurate principal and prediction comes out that can describes precisely the trend of corrosion rate at a specific atmosphere condition. This is because, there is variety of atmosphere corrodents existed and it varies time to time and place to place. Therefore, the prediction and estimation of steel corrosion becomes harder and uncertainty. Moreover, the global warming and high level of pollution rate in recent years would cause disparity increase between the actual and estimate corrosion rate. The difficulty and uncertainty of the corrosion rate for long term and short term prediction is a issue of global concern as the total annual direct cost of corrosion is played an important role in the gross domestic product of a nation.

A research from J. G. Castano et al on the atmospheric corrosion of carbon steel in Columbia found that the mass loss of the carbon steel is increased and tended to stabilize over time (Castano et al, 2009). However, this result may changes at different location, seasons, exposure position and angle, and other factors such as washing and

precipitation effect of rain and wind velocity. Therefore, an exposure test at a specific location and specific environment is always required in order to get an accurate estimation and prediction data of corrosion behavior at the region. An accurate prediction of corrosion behavior of steel are always preferred for material selection and as references to choose an appropriate corrosion control method as well as the protection step in order to prolong the life of metallic structures and components exposed to the environments.

1.3 OBJECTIVES OF STUDY

i. To study the outdoor and indoor atmospheric corrosion of AISI 1010 steel over time of exposure in University Malaysia Pahang, Pekan.
ii. To investigate the effect of outdoor and indoor atmospheric corrosion on the corrosion rate and microstructure of AISI 1010 steel.

1.4 SCOPE OF PROJECT

i. Specimen validation.
ii. Specimen preparation and exposure rack fabrication.
iii. Exposure test of specimens to outdoor and indoor atmosphere in University Malaysia Pahang, Pekan by manipulate the exposure time.
iv. Atmospheric evaluation.
v. Mass loss and corrosion rate analysis.
vi. Microstructure analysis by using Scanning Electron Microscope (SEM).

1.5 SIGNIFICANT OF STUDY

Results obtained from this study can contribute to the existing data of indoor and outdoor atmospheric corrosion and as a reference for University Malaysia Pahang which is located at Kuala Pahang, Pekan areas. This result is important especially for material selection on structural design near the region. Besides, the data obtained can also leads an ideas and guides for proper corrosion control and protection steps in order to enhance the life of service of a component and structure. This is beneficial in term of the

decreasing of the corrosion protection cost while the service life of the component and structure can be extended.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Corrosion is a natural tendency of material's composition element return to their most thermodynamically stable state by undergoing chemical or electrochemical reaction that breaks the chemical bonds (Schweitzer, 2007). In other word, for most of the metallic material, corrosion is defined as the formation of oxides or sulfides on the metallic material and it is resulting deterioration and degradation the properties of the metallic material. All metallic materials are chemically unstable in air and air-saturated water at ambient temperatures except gold; however, application of metal is still preferred and desired as metal give a superficial impression of permanence in services.

Corrosion is both costly and dangerous which lead to failure in plant, infrastructure and machine. Billions of cost had been spent annually for corroded structures, machinery, and components, including metal roofing, condenser tubes, pipelines, and many other items. For structural system such as ships, offshore platform, pipelines and pressure vessel there usually are two critical design criteria (Melchers, 2005). The first is the surface and general corrosion in which it is a function of the amount of material loss. Secondly, the essential of localized and in particular due to pitting corrosion. With the presence of oxygen and water, iron and steel were corroded under normal circumstances. However, without the presence of any of these materials, corrosion process will not occur, which means there will no electrochemical reaction taking place and no degradation on the material.

Corrosion process can be classified and occurs through two main types of processes due to its nature of the corrosion process and factors affecting it. These two types of corrosion processes are chemical corrosion and electrochemical corrosion. In this chapter, atmospheric corrosion of electrochemical corrosion process will be focused.

2.2 CORROSION OF CARBON STEEL

Steel are the most widely used and applied of engineering steel especially for structural system. The advance properties of steel such as strength, formability, abundance, and least expensive are always desired and makes them a prior selection in engineering design. Therefore, atmospheric corrosion of carbon steel has always been of prime interest for engineers. Steel corrosion is primarily affected by general or uniform corrosion. Pure iron generally exists as a body-centered cubic (BBC) structure at temperature below 910 ^{o}C and 1400 ^{o}C. In the intermediate of this temperature range, pure iron presents as face-centered cubic (FCC) structure. At temperature above 1400 ^{o}C and below 910 ^{o}C, the solutions in BCC iron are denoted as δ-ferrite and α-ferrite respectively. On the other hands, in the intermediate range, the solution of FCC iron is denoted as γ-austenite. Figure 2.1 is the phase diagram of iron-carbon system which showing the phases that are present in the steel of various carbon contents over a range of temperatures under equilibrium conditions.

However, steel is basically exists as an alloy of iron and carbon with the carbon content up to approximately 0.1-1.0 mass % and called as plain carbon steel (Talbot, D. E. J. and Talbot, J. D. R, 2007). These plain carbon steel can be classified into 3 different types which include low, medium and high carbon steel. The carbon contains for each type of carbon steels is different in which for low-carbon steel, the carbon content is below 0.2 mass % while for medium and high carbon steel the carbon content are 0.2-0.5 mass % and above 0.5 mass % respectively (Smith and Hashemi, 2006 and Cardarelli, 2008). The presence of carbon without substantial amounts of other alloying element is primarily responsible for the properties of carbon steel. Figure 2.2 (a) below shows the micrograph of low carbon AISI/SAE 1010 steel which showing a matrix of ferrite grains which is white etching constituent and pearlite which in dark etching constituent. On the other hands, Figure 2.2 (b) and (c) show the micrograph of medium

carbon AISI/SAE 1040 steel and high carbon AISI/SAE 1095 steel. For the medium carbon steel, however, the ferrite grain is finer and the ratio to pearlite is lower compared to low carbon steel. Moreover, for the high carbon steel, the micrograph shows matrix of pearlite and some grain boundary of cementite which in dark etching constituent.

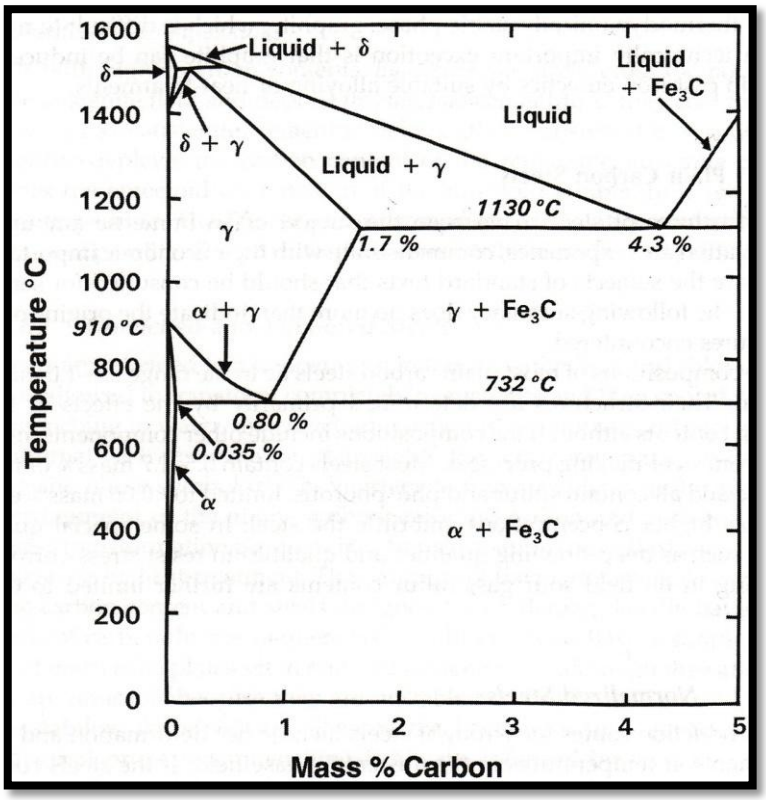
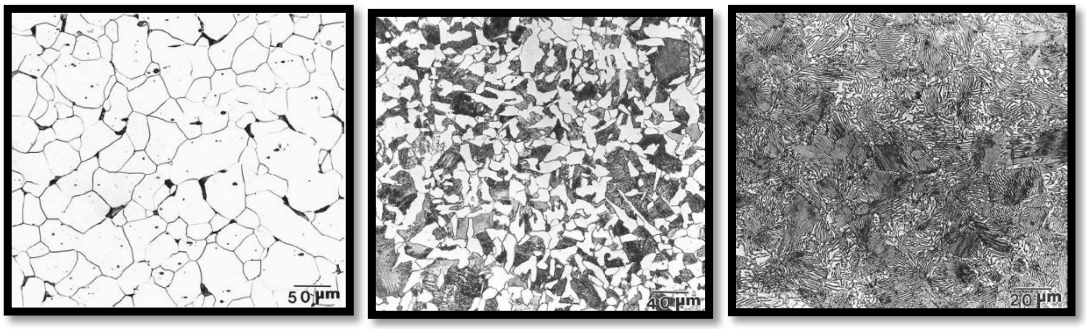


Figure 2.1: Equilibrium phase diagram for the iron-carbon system. α = α-ferrite; δ = δ-ferrite; γ = austenite; Fe_3C = cementite

Source: Talbot (2007)



(a) (b) (c)

Figure 2.2: Micrograph of carbon steels. (a) Low carbon AISI/SAE 1010 steel; (b) Medium carbon AISI/SAE 1040 steel; (c) High carbon AISI/SAE 1095 steel

Source: Bramfitt (2002)

Atmospheric corrosion of steel varies with time and differs from location to location. These variables include change of climate season, atmospheric pollutants, temperature cycles and initial conditions and orientations of the iron or steel surfaces. In industrial atmospheres, sulfuric acid is present while in both sea shore and urban, higher electrical conductivity of the rain and the tendency to form soluble chlorides or sulfates would accelerate the corrosion process. However, longer exposure time would bring lower corrosion rates which can be seen as formation of protective corrosion products. (Gil et al, 2010). For some alloy steel such as weathering steel which produced by alloying carbon steel with copper, chromium, nickel, phosphorus, silicon and manganese, their corrosion rate will becomes stabilized in three to five years after a protective film or patina is form that is dark-brown to violet on the surface. Patina film is a tightly adhering corrosion product on the surface of the steel that hardly be wiped off. In rural area, the formation of patina film is relatively slow where there is little or almost no pollution in rural. However, in areas that have high pollution level of SO_2 such as industrial area, loose particles are usually formed instead of patina. These loose particles do not offer protection against continued corrosion. Besides, in marine area, chloride is presented in atmosphere and the protection film will not be formed. Hence, in this condition, the corrosion rate of the alloyed steel is equivalent to those unalloyed steel.

2.3 ATMOSPHERIC CORROSION

Atmospheric corrosion is an electrochemical process taking place in corrosion cells rather than a direct chemical attack. Besides, atmospheric condition such as relative humidity, temperature, pollutants, salinity, etc plays a significant and essential role in the rate of corrosion and its behavior (Natesan et al, 2006 and Katayama, 2005). In particular, the most aggressive conditions that result in serious atmospheric corrosion of metals are found to be tropical, subtropical matine environment (Li et al, 2010). Atmospheric corrosion is the result of conjoint reaction of base metal, oxygen and water for the oxidation of iron and reduction of an oxidizing agent occur. Water acts as the electrolyte in order to transfer electrons and charges. However, with the absence of water, the metal corrodes at a negligible rate. The moisture from the atmosphere is the common electrolyte associated to atmospheric corrosion. The exits of dust and contaminants from the atmosphere such as sodium chloride, sulfur dioxide and carbon dioxide will accelerate the corrosion process rate. In this section, the types of atmospheric corrosion and its mechanism will be discussed.

2.3.1 Types of Atmospheric Corrosion

Atmospheric corrosion can be separate into 4 major types according to their corrosion rate, environment, atmospheric condition, and geographical as well. Although other types of corrosion such as urban, tropical and arctic can be included but the main concern are on the 4 major types of corrosion. This is due to their causes of tremendous and significant annual economic losses to a country. Many researchers have examined the corrosion rates of metal which is exposed to different atmospheric types and shown that corrosion rates are higher in marine and industrial environments than in rural areas (Upham, 1967). The 4 types of atmospheric are rural, marine, industrial and indoor have been described as follow:

i. **Rural**: The atmosphere in rural tend to have lower corrosion rate where it is generally contains no strong and aggressive chemical contaminants. The principal corrosive constituent in rural area is the moisture content, small amounts of carbon dioxide (CO_2) mostly from the combustion exhaust of vehicle

engine and sulfur oxide (SO_x). However, arid or tropical environment are the extreme cases in this type of corrosion. With the additional of high average temperature, high relative humidity, intense sunlight and long period of condensation during the night time are the main factors of higher corrosion rate in arid and tropical environment.

ii. **Marine**: The main factor that causes high corrosion rate for coastal atmosphere is the deposition of marine aerosol particle which produced from the breaking of waves. The turbulence that accompanies this phenomenon introduces air bubbles into the water, which subsequently burst and launches sea salt particle into the atmosphere (Feliu et al, 2001). Higher winds from coastal shores that bring together with the deposition of fine droplets of crystal formed by evaporation of spray from the sea water and increase the presence and increase the presence of sodium chloride (NaCl) content in the marine atmosphere. The presence of sodium chloride (NaCl) near costal shore increases the aggressiveness of the corrosion rate. However, the quantity and deposition of sodium chloride content in the atmosphere is typically decreased with distance to the shore and it is also highly affected by the wind current.

iii. **Industrial**: The atmosphere in industrial are associated with many sulfur oxide (SO_x) and nitrogen oxides (NO_x) produced from the burning of fossil fuel and chemical waste. These contaminants may convert into acid film on exposed surface with the present of moisture, dew or fog such as sulfurous or sulfuric acid. The critical relative humidity, above which metals corrode, drops to about 60 percent when these airborne pollutants are deposited on the exposed metal surface (Syed, 2006). Besides, other contaminants such as dust particle may also accelerate the corrosion process (Bartholomew and Shifler, 2007). The dusts adhere on the metal surface will absorb water and prolonging the time of wetness. The pollution level in the industrial area is a significant factor in promoting and accelerating corrosion (Upham, 1967).

iv. **Indoor**: In indoor condition, the corrosion rate is considered as very low due to the mild atmosphere behavior. However, higher values of corrosion rate were

found during the initial stages of the exposures (Gil et al, 2010). Nevertheless, the presence of contaminant such as HCHO and HCOOH in the indoor atmosphere can transform ambient air into corrosive condition. These indoor corrosion stimulants are come from the tobacco and cigarette smoke, combustion of biomass, adhesives and plastics.

2.3.2 Mechanism of Atmospheric Corrosion

Atmospheric corrosion products of iron comprised of various types of oxides, hydrated oxides, oxyhydroxides and miscellaneous crystalline and amorphous substances (Morcillo et al, 2011). These oxides are the results of the chemical reaction between the material and the atmosphere. Such substances can be either endogenous product or exogenous products. The formation of the type of oxides depends on the composition of the iron material and the atmosphere type to which it is exposed to.

Atmospheric corrosion can separate into 2 categories due to the form of water present which are damp atmospheric corrosion and wet atmospheric corrosion (Schweitzer, 2007). Damp atmospheric corrosion take place in the presence of water vapor layer as caused in fog, humidity or dew while wet atmospheric corrosion occurs when rain or other form of bulk water are present with exist of corrosive pollutant. The rate of atmospheric corrosion is directly influenced by the amount of water contact on the surface of the metallic material.

Electrochemical process occurs in corrosion cell must include of a metal anode and cathode, an electrolyte in contact with anode and cathode, and a metallic conductor between the anode and cathode. Atmospheric corrosion process takes place by electrochemical rather than chemical process. The initiation of an electrochemical corrosion process in atmospheric corrosion must with the presence of a thin film of electrolyte. The thin film electrolyte on the metallic surface formed under atmospheric exposure conditions after a certain critical humidity. The critical humidity level is not constant and it is depending on the corroding material, the tendency of corrosion products, surface deposits to absorb moisture and the presence of atmosphere pollutants

(Tullmin and Roberge, 2000). Figure 2.3 shows the schematic of atmospheric corrosion mechanism.

In the presence of thin electrolyte film as shown in Figure 2.3, the atmospheric corrosion proceeds by balancing the anodic and cathodic reaction (Tullmin and Roberge, 2000). Firstly, in the anodic process, the major component of metal, iron (Fe) at the surface of the material beneath the thin electrolyte film undergoes an oxidation reaction. The iron atom loses electrons and becomes a positively charged ion as shown in Equation 2.1. On the other hands, in the cathodic process, it is involving the reduction process of oxygen in water. The electrons of oxygen are consumed as shown in Equation 2.2. This makes sense that the anion of hydroxyl combines with the iron cation and form the iron (II) hydroxide as shown in Equation 2.3.

Anodic procress: $Fe \rightarrow Fe^{+n} + ne^-$ (oxidation) (2.1)

Cathodic process: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ (reduction) (2.2)

Overall corrosion of iron: $2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2$ (2.3)

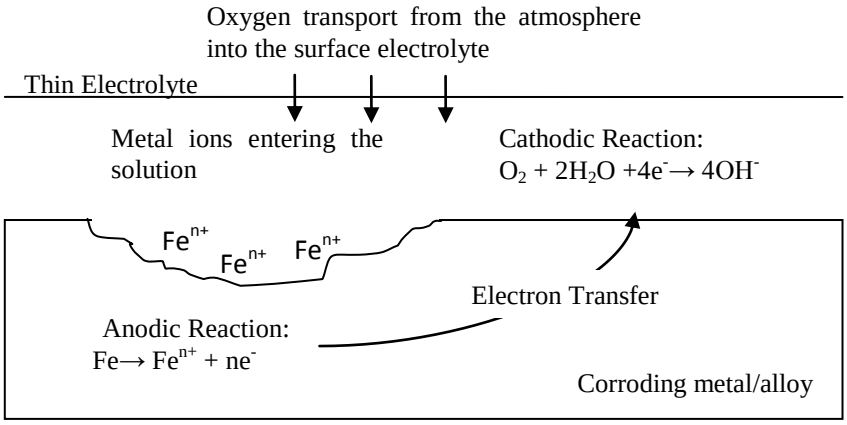


Figure 2.3: Schematic of atmospheric corrosion mechanism

Adapted from: Tullmin (2000)